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LABORATORY PHOTOMETRIC MEASUREMENT OF PARTICULATE SOILS OUT TO VERY LARGE PHASE ANGLES

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Introduction: The use of photometric methods in planetary geology has advanced substantially in the past few decades, largely due to the development and continuing refinement of physically motivated radiative transfer models, such as Hapke's[1,2,3] equation. These models seek to describe the angular reflective behavior of rough particulate surfaces in terms of surface physical properties. The properties are themselves characterized by model parameters such as average particle single scattering albedo ϖ_0, the average topographic slope angle of macroscopic surface roughness, θ, parameters h and B_0 which relate the angular width and amplitude of the opposition surge, respectively, to the surface state of compaction and optical properties of particles, and parameters which describe the angular scattering properties of average particles, that is, the particle phase function, $P(\alpha)$.

Until recently, most applications of photometric theory have involved only relative comparisons of photometric parameters derived from spacecraft and telescopic observations of different planetary surfaces. However, as demands to extract more detailed physical information from photometry arise, quantitative interpretation of Hapke parameters becomes crucial. Applications such as estimating mineral abundances in multicomponent soils on the basis of spectral features rely heavily upon accurate determinations of particle single scattering albedos and phase functions. Since $P(\alpha)$ and ϖ_0 are closely related[4], an inaccurate understanding of one can adversely affect our confidence in the other[5].

Considerable study has been devoted to the phase function behavior of real particles. Most studies that examine scattering behavior out to large phase angles consider only scattering properties of dispersed particles separated by large interparticle distances. It is generally assumed that the effective phase functions of the particles remain unchanged when particles are brought into mutual contact, as in a soil or regolith. It is not presently clear how radiant energy involved in scattering processes such as diffraction (which creates a strong forward scattering lobe in $P(\alpha)$ for systems of dispersed particles) is redistributed when particles are brought into mutual contact. Recent investigations[6,7] of very large isolated particles suggest that even relatively low-albedo particles should exhibit forward scattering components of $P(\alpha)$, however, detailed forward scattering behavior in actual particulate surfaces has been studied principally for high-albedo materials such as snow and frost[8].

Objectives: In the present study, our objectives are to develop the laboratory methods and tools to conduct photometric observations of dark particulate samples over a large range of phase angles ($0° \leq \alpha \leq 160°$), and to demonstrate whether forward scattering behavior can be seen in a surface constructed of low-albedo material. We also examine the adequacy of various model formulations of $P(\alpha)$ to describe the effective scattering properties of our sample.

Experimental Approach: The Cornell Goniometer was constructed over 15 years ago to study the spectrophotometric properties of particulate samples over visible and near-infrared wavelengths (0.4-1.2 μm) at a variety of photometric geometries. We have modified the instrument to extend its usable range of incidence (i), emission (e), and phase (α) angles. A beamsplitter attachment was constructed to observe opposition surge behavior over $0° \leq \alpha \leq 18°$, with the device, and at overlapping phase angles ($\alpha > 4°$) with the device removed. In addition, we invented a variable-geometry elliptical iris to restrict the collimated incident light beam so that it projects onto the sample as a circular disk even out to large incidence angles. This device enabled observations at simultaneously large incidence and emission angles. At emission angles greater than about 60°, the detector field of view extends beyond the illuminated portion of the sample dish. We have discovered that the appropriate correction for this geometric effect can be obtained directly by measuring the sample's reciprocity. If the reflectance behavior of a given sample is represented as $r(i,e,\alpha)$, then reciprocity principle states that $r(i,e,\alpha)/\cos(i) = r(e,i,\alpha)/\cos(e)$. To use this principle, we fix the detector at a given emission angle (for example $e=0°$) and vary i from 0°-77°. We then make the reciprocal measurement (fix $i=0°$ and vary e from 0°-77°). The correction factor, $C(e,\alpha) = (\cos(e)/\cos(i))(r(i,e,\alpha)/r(e,i,\alpha))$, is then unity for all $e < 60°$, and systematically increases with increasing e elsewhere.

Results: For our sample, we have chosen a sieved 75-149 μm sized fraction of crushed augite. The normal reflectance of this material (relative to $BaSO_4$) is typically 10% at $\lambda=0.5$ μm. 460 observations of this sample were obtained in the scattering plane over $0° \leq i \leq 85°$, $0° \leq e \leq 77°$, and $0° \leq \alpha \leq 162°$. We can express these observations in terms of particle phase function, $P(\alpha)$, as follows[5]: For a macroscopically smooth ($\theta=0°$) low albedo surface in which multiple scattering of light is not significant we isolate the product, $F(\alpha)=(1+B(\alpha))P(\alpha)$ of Hapke's opposition surge function and $P(\alpha)$ as $F(\alpha) = 4\,(\mu_0+\mu)\, r_m(i,e,\alpha)/(\varpi_0\mu_0)$, where $\mu_0=\cos(i)$, $\mu=\cos(e)$, and $r_m(i,e,\alpha)$ is the measured bidirectional reflectance of the sample. We eliminate the constant $4/\varpi_0$ by normalizing to our observation at $F(0°)$. Fig. 1a shows a plot of $F(\alpha)$ vs. α for our augite sample. The opposition surge at small phase angles can readily be distinguished from the rest of the $F(\alpha)$ curve. At $\alpha > 120°$, $P(\alpha)$ clearly exhibits a strong forward scattering lobe.

Analysis: We have conducted least-squares fits of a variety of commonly-used $P(\alpha)$ models. A simple, one-term Henyey-Greenstein function, often used in planetary applications, is inadequate for describing $P(\alpha)$ at all phase angles. As Fig. 1a shows, a linear combination of two one-term Henyey-Greenstein functions appears to be the simplest model to yield good results. Our least squares fit gives particle phase function asymmetry factors of $g_1=-0.31$ and $g_2=+0.40$ for the forward and backward lobes, respectively, with the backward scattering component contributing 36% to $P(\alpha)$. The corresponding value of $\varpi_0=0.20$. Opposition surge parameters $h=0.027$ and $B_0=0.59$ are well-constrained by our data.

Fig. 1b illustrates how macroscopic surface roughness may reduce the detectability of forward scattering behavior in planetary regoliths. We have used our best-fit Hapke parameters to predict phase curves for hypothetical crushed augite-covered planets having varying degrees of macroscopic roughness ($0° \leq \theta \leq 60°$). Phase curve data for the Earth's moon is shown for comparison. As roughness is increased, the phase curves become more strongly backscattering. While we have not chosen our sample to simulate lunar regolith in any way, the augite phase curve for $\theta=50°$ is remarkably similar in shape to the lunar phase curve. Since macroscopic roughness can often be independently constrained by limb-darkening across a planetary disk, disk-resolved photometric observations should help in distinguishing the presence of forward scattering from planetary phase curves.

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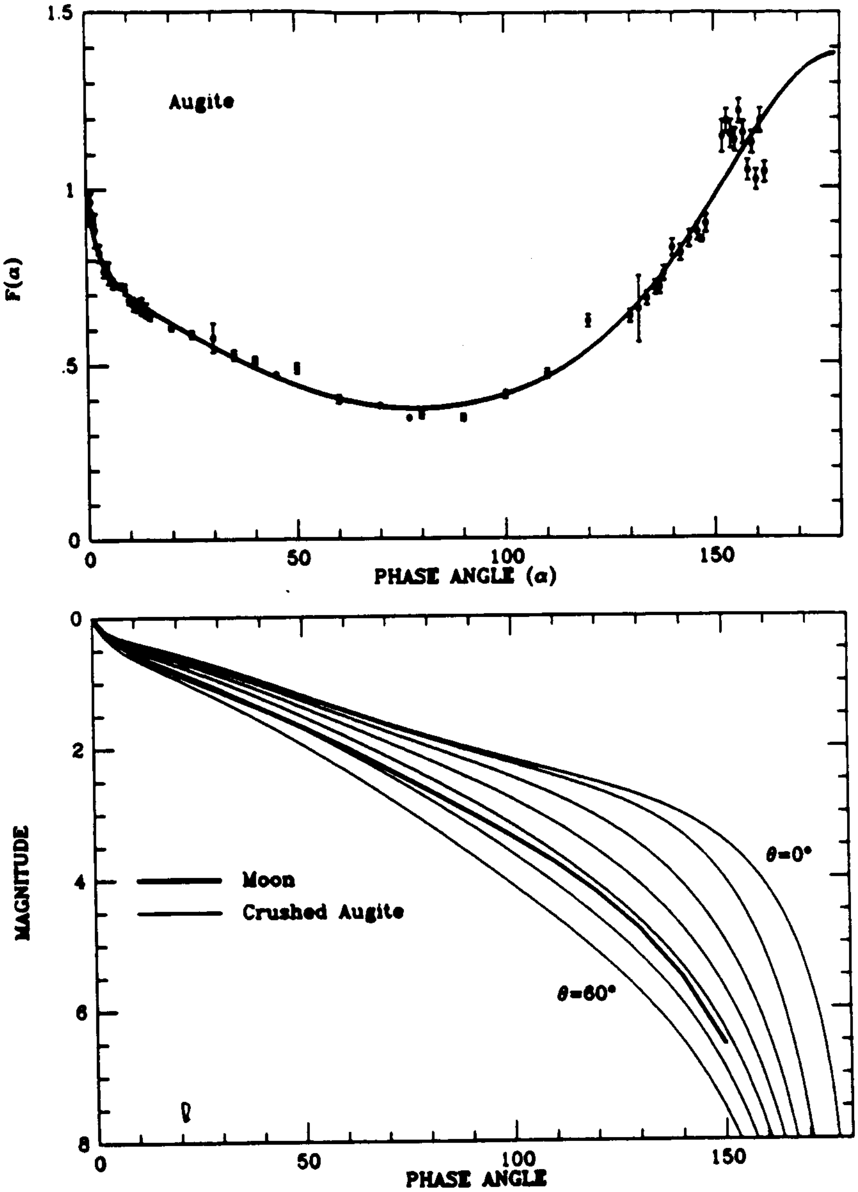

Fig.1: a) F(α) vs. α for crushed Augite sample. b) Predicted phase curves for hypothetical crushed-augite covered planets with different roughnesses. Lunar phase curve shown for comparison.

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